16^{th} Marcel Grossmann Meetings Meeting July 5-10, 2021

The Ginger project - preliminary results

Giorgio Carelli, University of Pisa & INFN-Pisa

July 8, 2021

Overview

Overview

- The Sagnac effect
- The ring laser gyroscope
- GINGER, array of RLG for fundamental physics
- our prototypes and recent result

absolute rotation measurement

a very special instrument

General Relativity and Lorentz Violation

GINGERINO's sensitivity

The Sagnac Effect

- For pedestrian: when you run on top of a turning table the time necessary to complete the turn depends on the direction
- For scientist: the confrontation of the time required to complete a closed path in the two opposite directions depends on not reciprocal effects

Sagnac effect: inertial angular rotation rate Ω

$\Omega \propto \delta t$ proportionality constant depends on the geometry

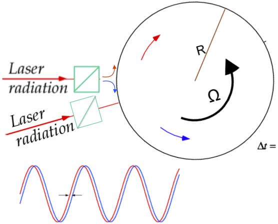
a very special instrument

absolute angular rotation $\rightarrow$ rigid apparatus, no moving parts

The Sagnac gyroscopes

- Different schemes: using light (resonant cavity or optical fibers), cold atoms, or helium superfluid.
- a special kind of interferometer
- the sensitivity record belongs to the Sagnac gyroscope based on active square cavity (ring laser gyroscope RLG, $ASD \leq 10^{-9} - 10^{-12}$rad/s, 1 s).

$$\Delta\phi = \frac{8\pi A}{\lambda\, c} \vec{n} \cdot \vec{\Omega}$$



$$t = \frac{2\pi R}{c - \Omega R} \qquad t = \frac{2\pi R}{c + \Omega R}$$

$$\Delta t = \frac{2\pi R}{c - \Omega R} - \frac{2\pi R}{c + \Omega R} \approx \frac{4\pi \Omega R^2}{c^2} = \frac{4\Omega}{c^2} A$$

$$\Delta\phi = 2\pi \frac{c\Delta t}{\lambda} = \frac{8\pi \Omega A}{\lambda c}$$

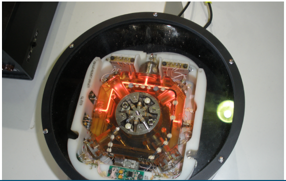
In general: $\Delta t = 4\frac{\vec{\Omega}\cdot\vec{A}}{c^2}$; $\Delta\phi = \frac{8\pi\vec{\Omega}\cdot\vec{A}}{\lambda c}$

for the RLG: $\omega_s = |\omega_{cw} - \omega_{ccw}| = \frac{4\vec{A}\cdot\vec{\Omega}}{\lambda p}$

A tool with large impact for applications

Applications

- inertial navigation
- measurement standards, for example angle
- rotational seismology
- earth rotation at different location, (daily and sub daily comp.)
- geodesy and geophysics



Fundamental science ?

Fundamental noise or fluctuations of photon beams (two identical beams trapped inside a high finesse cavity)
Lorentz violation and general relativity tests on earth (Lense Thirring and de Sitter) single station, no average, independent gravity map not required

Requirements: long term data stream and high sensitivity.
Which sensitivity?

RLG a very special instrument

- unattended continuous operation for months
- typically sub-prad/s sensitivity in 1 second of measurement
- very large bandwidth, fast response, in principle as fast as milli-seconds
- very large dynamic range. Since it is based on frequency measurement, the same device can record sub-prad/s variations and strong signals from near by earthquakes
- they can be oriented at will in order to reconstruct in 3D the angular rotation vector

GINGER (Gyroscopes IN GEneral Relativity)

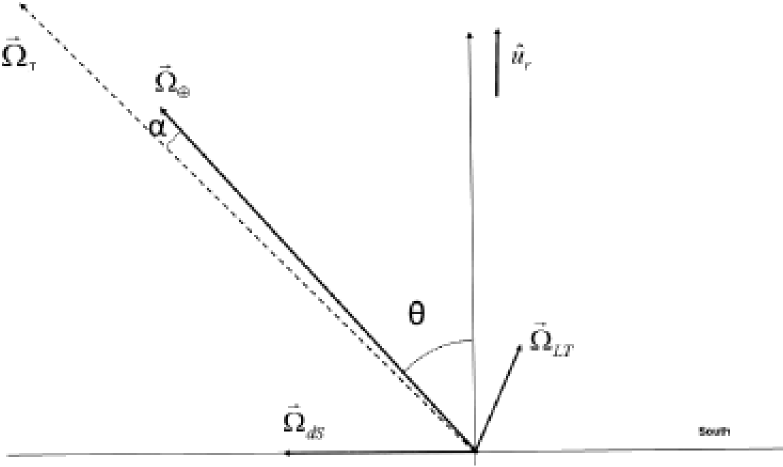
- GINGER is a project based on an RLG array (underground, isolated from external disturbances)
  GINGER aims to directly measure the Lense Thirring effect on the Earth
- Lense Thirring (and de Sitter) acts on the RLG as angular rotation vector summed to the Earth rotation rate.
- The kinematic component are independently measured by IERS with very high accuracy
- Main difference with existing measurements: fixed latitude, not averaged; synchronization of different clocks and independent gravity map are not required.
- You can discriminate among different theories, minimizing modeling

Lorentz Violation, PRD 100 (2019) 6, 064031

Jay Tasson, and coauthors, have pointed out that RLG can effectively contribute to the Lorentz Violation quest.
We note that the LV test pursued following Tasson calculation is looking at some modulated effect, so very high accuracy is not required.
We are in touch with Jay providing data samples useful for his students.

Sensitivity of 1 part in 10^9 of the Earth rotation rate would provide interesting measurements of two Lorentz-violating terms in the framework of the Standard-Model Extension.
In one case, sensitivities that are competitive with recent laboratory and perhaps solar system tests would result.
For the other term, measurements competitive with the best existing limits, which currently comes from radio pulsar studies, would result.

Lense Thirring and de Sitter at 45^o latitude



GINGER constraints... Capozziello et al.

Constraints taking into account Extended Theories of Gravity. From the weak-field limit of the theory, it is possible to relate the gyroscopic and Lense-Thirring effect with the parameters of the further degrees of freedom present in the theory. GINGER puts an upper limit to the first derivative of the function $f(R, R^{\mu\nu}R_{\mu\nu}, \phi)$ with respect to the second-order curvature invariant $R^{\mu\nu}R_{\mu\nu}$ obtaining $m_\gamma > 1.88 \cdot 10^{-6} m^{-1}$

Let's consider specific matter Lagrangian of Horava-Lifshitz gravity, a_1 and a_2 are parameters theoretically un-constrained. In the weak field limit, a relation between the two constants and the value of the effective gravitational constant G_{HL} can be found. From the LT term it is possible to obtain $0.999 G_N < G_{HL} < 1.001 G_N$ and a_1 and a_2 are fixed through data with the direct measurement.

S. Capozziello et al, Eur. Phys. J. Plus (2021) 136: 394

Sensitivity relative to Earth rotation rate

- de Sitter and Lense Thirring effects are function of the latitude **(multisite approach would be advantageous)**, but are independent from the gravity map of the Earth.
- Lorentz Violation, in the SME framework
- Gravitational waves exciting the Earth quadrupole moment
- space-time structure in the noise spectral density (Craig Hogan-Holometer)

Salvatore Capozziello

sensitivity windows $10^9 - 10^{13}$, low rate, DC and accurate, IERS required.

Jay Tasson

1 part 10^9 or better, fractions of hours

...here sensitivity is never enough..

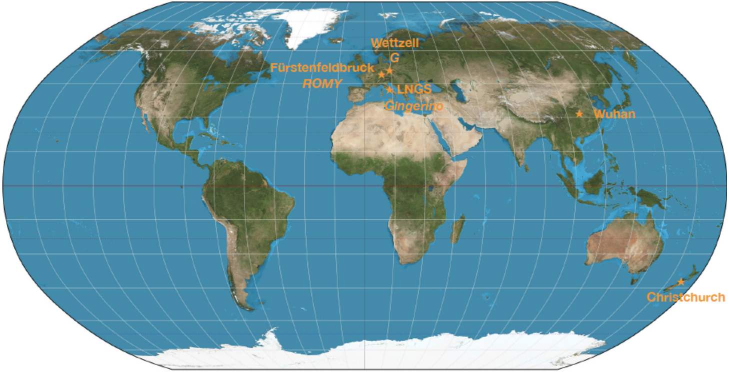
sensitivity better than 1 part 10^{12} at 1 hour frequency.very high frequency, MHz and high accuracy.

Watershed for fundamental physics

- Watershed between applications only and fundamental physics:
  - sensitivity higher than 10^{-9} of the Earth rotation rate $\Omega_{\oplus}$,
  - Operative in a continuous basis
  - **Accuracy** (not only sensitivity) is required for General relativity test
- GINGER in any case would provide data useful for geodesy (LoD), seismology and geophysics in general.

High sensitivity RLG gyroscopes

Large-frame optical gyroscopes in the world



High sensitivity RLG gyroscopes

At present several RLGs are operative:

G of the geodetic observatory of Wettzell,
ROMY , a 4 RLG array with 36m perimeter, in the geophysical observatory of Bavaria,
GINGERINO in the underground Gran Sasso laboratory, in Italy,
ER1 of the University of Canterbury, in NewZealand,
HUST-1 passive gyroscope at HUST, part of the TianQin project, at Wuhan in China.

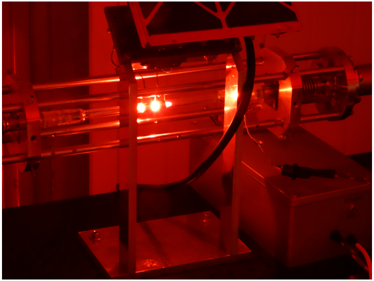
We are all in touch and collaborate

3D and Hetero-lithic RLG structure

- The best known RLG G, of the geodesic observatory of Wettzell, is based on a monolithic very rigid mechanical structure,
- We developed and studied RLG structures based on a modular mechanical design, which can be easily reproduced and aligned at will. Optical mechanical system can be used to measure and control the geometry.
- GINGERINO, HL structure, takes advantage of the underground location, which exhibits natural thermal stability and reduced anthropic activity.

Our prototypes: G-Pisa

...it was very hard to have G-Pisa working, but as soon as the gain tube had a bright red color life became easier....

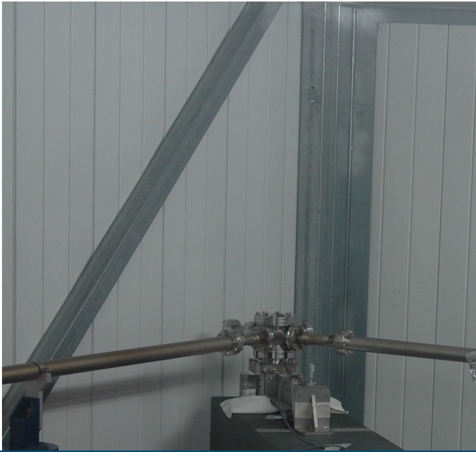


...2011 G-Pisa operative in the Virgo Central area, it has measured the effect of the strong wind on the central building. For one year, it has operated horizontal and vertical to measure tilts due to strong wind.

Our prototypes: GINGERINO

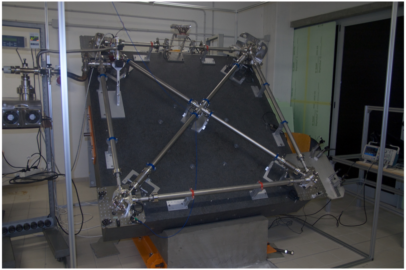
GINGERINO, 3.6m in side was the maximum size for a square cavity inside the tunnel.

...a lot of patience required... the signal of the beat note

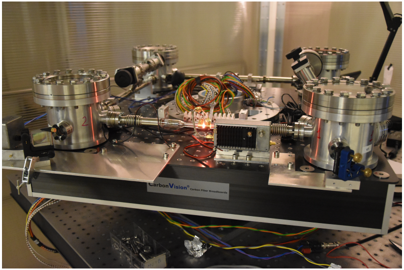


Our prototypes: GP2 and GLAS

GP2 1.6m side, in Pisa and used for tests, is oriented at the maximum Sagnac signal.



GLAS the INRIM goniometer, progetto premiale.



Why so few: The problem of the RLG

The use of the active cavity is extremely advantageous, but has the drawback that the response is affected by the non linear laser dynamic. We have elaborated an original analysis technique which takes into account the laser dynamic, and reconstruct ω_s using the available signals of the laser: the beat note ω_m, the intensities of the two laser modes (DC and at ω_m) and their relative phase.

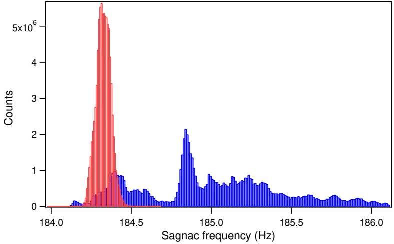


Figure: Distribution of the signal of GP2, with and without taking into account the dynamic of the laser

Eur. Phys. J. C (2019) 79: 573.
Eur. Phys. J. C (2020) 80: 163

Available signals

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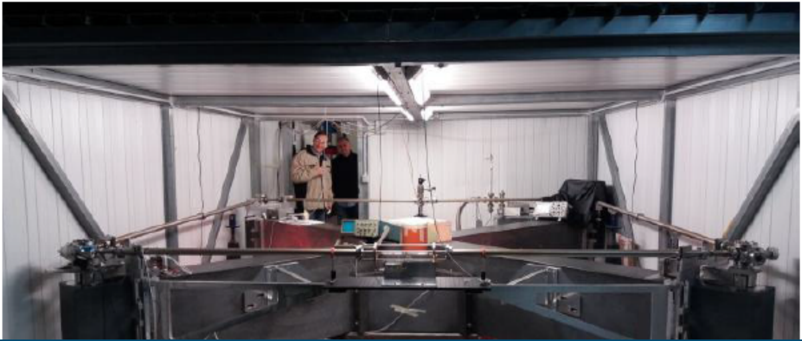
Signals:

Gyroscope signals: beat note ω_m, amplitude of the two modes I_1 and I_2, amplitude of the two modes at the beat note frequency IS_1 and IS_2, relative phase ε, power at the discharge GM

Environmental signals: Temperature, Pressure, Tiltmeter ζ_1 and ζ_2



The Earth: natural test-beam

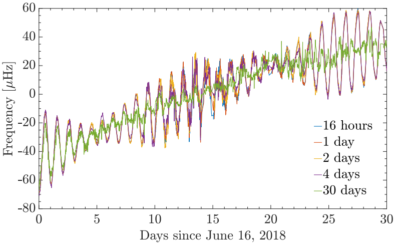
- RLGs are sensitive to the Earth global rotation (Ω_{geo}) and its variations: polar motion, Annual and Chandler wobbles, tides, crust deformations etc, all measured with very high accuracy by the international system IERS.
- This provides a "natural test beam" to investigate the characteristics and the sensitivity of GINGERINO.
- The true Sagnac signal ω_s is recovered taking into account the laser dynamic, and assuming that it is $\omega_s = \omega_{geo} + \omega_{local}$, where ω_{geo} indicates the scalar product of the total variations of the Earth with the RLG area vector, ω_{local} the signals of local origin, related to temperature fluctuations and local tilts.
- ω_s, ω_{geo} and ω_{local} are identified using linear regression and standard statistical means based on minimum square
- weak points of the apparatus and the sensitivity are investigated.

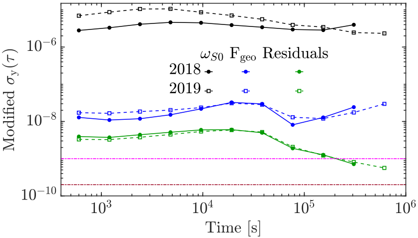
Linear regression

GINGERINO is running in a continuous basis, unattended and free running since 2017. We know that inside its data the global signal $\Omega_\oplus$ (independently measured by IERS, F_{IERS}) is contained. It contains also local disturbances ω_{local}, in principle due to geophysical phenomena or instrumental. Aim is to identify ω_{local} with a linear regression using the laser dynamic, the available environmental signals, temperature, pressure and tiltmeters signals $\zeta_{1,2}$ to reconstruct the global signal F_{IERS}.

$$\omega_s = CAL \cdot F_{IERS} + LD_T\mu + \omega_{local}$$
$$F_{IERS} \propto \vec{A} \cdot < \vec{\Omega}_\oplus > + CW + PM$$
$$\Omega_\oplus = < \Omega_\oplus > + \Delta\omega_3$$

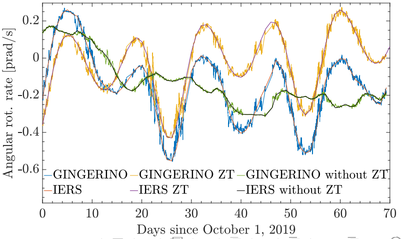
CW and PM indicate the effect of the Annual and Chandler wobble and the daily polar motion. IERS data are used to cross calibrate and evaluate the absolute orientation and the effective scale factor SF in an arbitrary point T_0, to evaluate CAL.





sensitivity limit 40 frad/s after 3.5 integration days: meaningful for GR test and Lorentz violation study. Please note that MAD is still decreasing.

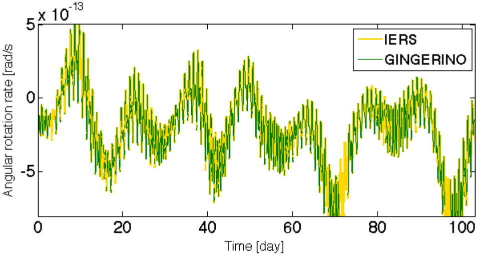
F_{geo} is F_{IERS} reconstructed by the linear regression.



Eur. Phys. J. C (2021) 81: 400

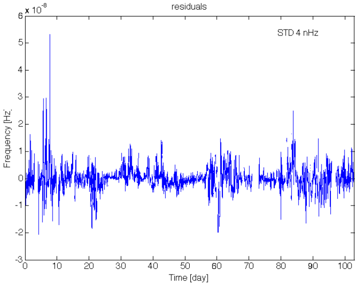
$\zeta_{1,2}$ plays a dominant role in the identification of ω_{local}. More explanatory variables are added to the linear regression, obtaining:residuals gaussian distributed, typically STD 10 – 4nHz (below frad/s)

estimation of the sensitivity limits using two sinusoidal signals added to the signal and to the LR: period 40 and 0.5 days, sensitivity of the order of 0.3nHz (0.01frad/s).

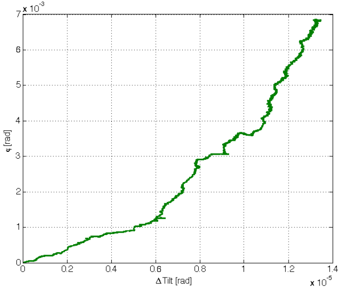


The disturbances have instrumental origin

Typical residuals, STD 4nHz.



ω_{local} is instrumental, when the monument tilts the mechanical structure of GINGERINO rotates. Improvement of the heterolithic mechanical design required.



Very important to remark

- IERS provides the local angular rotation with wobblers, tides and deformations. The analysis method is not predictive, but it is good to investigate the apparatus.
- The level of precision with which the different terms of the linear regression, and the residuals indicate 0.1frad/s sensitivity.
- **our main concern about this result is: it looks too good....**

Fundamental limit problem

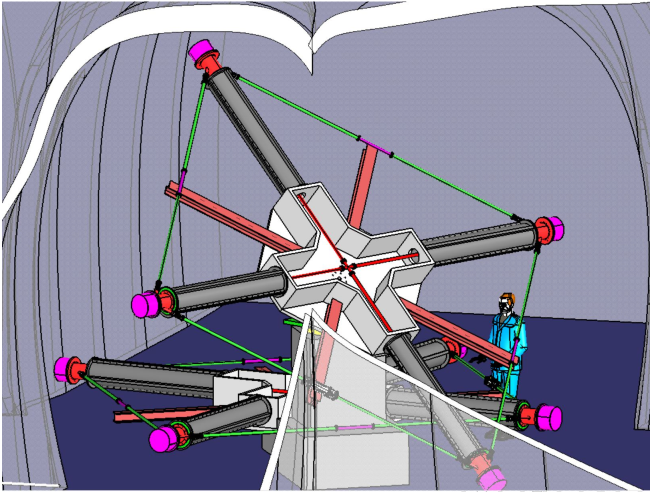
The debate around RLG sensitivity is still active, mainly focusing to very small RLGs; so far the limit for large frame, high sensitivity RLGs is considered to be the shot noise due to spontaneous emission of laser atoms. However, in our case the Sagnac frequency falls inside the gain curve of the laser medium and, possibly, a study of the quantum noise of the entire process, laser emission/cavity/detection,is required. The sensitivity we observe is a factor 1000 below the shot noise due to spontaneous emission of the laser atoms.

Ready to proceed with the GINGER proposal

- We have concluded our preliminary work toward GINGER and we are working for the GINGER proposal.
- The first target was 1% of the Lense Thirring, the speculation about the sensitivity indicates the feasibility of 0.1%, a factor 10 improvement.
- The main difficulty is to subtract the Earth kinematic components, this implies to constantly have the absolute orientation of the RLG.
- The RLG at maximum signal has the advantage to be insensitive to small orientation changes, and using its data it is possible to monitor the orientation of the other RLG of the array with respect to the absolute orientation of the total angular rotation vector.

GINGER, Gyroscopes IN GEneral Relativity

The RLG at the maximum signals provides $|\Omega_\oplus|$ and the relative orientation of the other two RLG with the Earth rotation axis.



People involved

INFN People
Angela D.V. Di Virgilio, Umberto Giacomelli, Andrea Simonelli, Giuseppe Terreni, Andrea Basti, Nicolò Beverini, Giorgio Carelli, Donatella Ciampini, Francesco Fuso, Enrico Maccioni, Paolo Marsili, Carlo Altucci, Francesco Bajardi, Salvatore Capozziello, Raffaele Velotta, Alberto Porzio, Antonello Ortolan
Gran Sasso laboratory, Sezioni di Pisa, Napoli and Legnaro
University of Pisa and Naples

INGV people
Gaetano De Luca, Roberto Devoti, Giuseppe Di Stefano
and Aladino Govoni

In discussion with Urs Hugentobler, Heiner Igel LMU München
K. Ulrich Schreiber TUM München.

Near future plan and conclusions

The measurement of the Earth angular rotation rate, in order to be fruitful for a fundamental physics test, has to have sensitivity of 1 part in 10^9 or better.
The most recent analysis of the GINGERINO data indicates a sensitivity better than 1 part 10^{12}, i.e. 0.1% of the LT term.
Accuracy is absolutely necessary.

GINGER has been designed using one of the RLG at the maximum Sagnac signal, in order to provide a measurement limited by the RLG sensitivity only. The RLG at maximum gives the orientation of the other two with respect to the axis of rotation. This special RLG requires a dedicated alignment procedure.
Rotation reconstruction based on RLGs only.